

**DECARBONIZATION OF TOLL PLAZAS: IMPACT ASSESSMENT OF TOLL COLLECTION
SYSTEM MANAGEMENT**

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Abstract

Transport climate change impacts have become a worldwide concern. The use of Intelligent Transport Systems (ITS) could contribute to a more effective use of resources in toll road networks. Management of toll plazas is central to the reduction of greenhouse gas (GHG) emissions, as it is there that bottlenecks and congestion occur. This study focuses on management strategies aimed at reducing climate change impacts of toll plazas by managing toll collection systems. These strategies are based on the use of different collection system technologies – Electronic Toll Collection (ETC) and Open Road Tolling (ORT) – and on queue management. The carbon footprint of various toll plazas is determined by a proposed integrated methodology which estimates the CO₂ emissions of the different operational stages at toll plazas (deceleration, service time, acceleration, and queuing) for the different toll collection systems. To validate the methodology, two main-line toll plazas of a Spanish toll highway were evaluated. The findings reveal that the application of new technologies to toll collection systems is an effective management strategy from an environmental point of view. The case studies revealed that ORT systems lead to savings of up to 70% of CO₂ emissions at toll plazas, while ETC systems save 20% comparing to the manual ones. Furthermore, queue management can offer a 16% emissions savings when queue time is reduced by 116 seconds. The integrated methodology provides an efficient environmental management tool for toll plazas. The use of new technologies is the future of the decarbonization of toll plazas.

INTRODUCTION

Climate change impacts have become a worldwide concern. In recent years, many different policies have been enacted in an attempt to reduce CO₂ emissions. A significant share of world CO₂ emissions is produced by the transport sector, accounting for 23% of overall CO₂ emissions from fuel combustion and 15% of overall greenhouse gas (GHG) emissions at a global level (1). Road transportation represents the bulk of transport emissions, some 75% worldwide (2). In Spain, increasing transportation demand – especially for road-based modes – is the main reason for the rise in GHG emissions (3). From 1990 to 2009, road traffic volume in Spain has increased by 94%, consequently, GHG emissions from road transportation have risen by 65% in that period (4, 5). The economic crisis, however, which has led to a decrease in road transportation activity, is having the positive environmental impact of reducing GHG emissions.

This study focuses on management strategies aimed at reducing the energy consumption of toll road networks by removing bottlenecks and congestion points. One way that this problem can be addressed is by incorporating Intelligent Transport Systems (ITS) which could contribute to improving driving behaviors by reducing acceleration and deceleration, idling, traffic congestion, etc. Toll plazas are key to any plan to reduce the GHG emissions of toll road operations. Through the use of intelligent payment systems, – Electronic Toll Collection (ETC) or Open Road Tolling (ORT) –, service time (the time it takes to complete a transaction at a toll booth) and queuing time are minimized. This paper will analyze the Spanish toll network, which is 3,024 km in length and makes up 22.4% of the total motorway network. Traffic in the toll network has increased by about 60% between 1990 and 2010 (5). A look at the different toll collection systems available on the Spanish toll road network reveals that ETC is available in all toll plazas in Spain, with 1,417 systems installed. Moreover, since the implementation of the ETC system, its use has been increasing and currently represents 21% of all toll payments (6).

In this context, the primary objective of this research is to analyze the carbon footprint (total amount of CO₂ and other GHGs expressed in tones CO₂ equivalent) of toll plazas which offer a variety of toll collection systems. To this end, an integrated model has been proposed in order to estimate emissions produced during different operational stages (deceleration, service time, acceleration, and queuing). Secondly, a methodology – based on scenario-building – will be presented to assess the climate change impacts of different toll plaza management strategies that incorporate ITS. The proposed ideas were tested at two toll plazas on a Spanish toll road where a trial was carried out to obtain information on traffic characteristics, driving conditions and the design of toll services.

This paper is structured as follows. First, there is a literature review of studies which offer analyses of different toll collection systems and their respective emissions impacts. Then, the integrated methodological approach for estimating the CO₂ emissions at toll plazas is described and the management strategies for optimizing their carbon footprint are proposed. Finally, results are offered which support the design of new strategies and policies to reduce the climate change impacts of toll roads.

INTELLIGENT TRANSPORT SYSTEMS FOR IMPROVING TOLL PLAZA MANAGEMENT

Worldwide, more than 70,000 toll facilities process about 100 million vehicle passages per day. Most toll systems are still based on conventional payment methods, where vehicles must stop to pay the toll. These are called manual toll collection systems or “cash lanes” when there is an attendant for the collection of the fee. Also common are automatic toll collection systems or “automated lanes” in which the payment is made automatically by means of coin machines or card readers (e.g., cash, credit card, etc.) but does not require the participation of personnel. The main problems with these two payment systems are traffic queuing and congestion at the main-line toll barriers, which indirectly produce an increase in the overall energy consumption and climate change impacts of the toll road. Advanced toll collection systems, like ETC, can accurately identify specific vehicles passing through them and can be used to gather information about them. With this system, the driver must slow down to pay the toll, but does not need to stop. ORT systems combine ETC technologies and highway traffic control: they eliminate the need to

pass through a physical plaza and speed is therefore not affected by payment. ORT is the best available system, as it is cheaper, safer, more efficient, and more environmentally-friendly than other toll collection techniques. The methodology is tested at two main-line toll plazas of a Spanish toll highway.

The various payment systems have differing impacts on energy consumption and CO₂ emissions. Some policies around the world promote the implementation of ITS technologies to reduce the negative impacts of operational toll plazas. In the United States, the 75 largest metropolitan areas have been working to incorporate ITS infrastructure into their toll collection systems since 1996 (7). In the European Union, the Directive 2004/52/EC (8) and its implementation plan 2009/750/EC (9) aim to achieve the interoperability of all electronic road toll systems with the goal of compatibility among all toll systems. This directive may, however, compromise the smooth operation of the EU internal market and the achievement of transport integration objectives. ITS aim to respond to the reality of transport needs by facilitating the immediate exchange of information, resulting in a more effective use of resources and more sustainable transport operations.

Research in this field has examined the potential effect of the introduction of ITS technologies on the environmental impacts of toll plazas. Most of the studies have focused on the reduction of air pollution by the implementation of ETC in toll plazas. Margarida *et al.* (10) compiled the most significant studies related to the analysis and modeling of the emissions impacts of toll roads from the 1990s to 2005. Their impressive work revealed that several models had been developed to describe traffic behavior at toll plazas, but that there was a need to introduce a vehicle emissions estimation module.

Margarida *et al.* (10) developed a methodology to quantify the traffic and emissions impacts of toll facilities on urban corridors. The approach is based on experimental measurement and attempts to explain the relationships between various operational variables (stops, queue length, and emissions). One of the results was that the use of ETC systems could reduce CO₂ emissions by 70% with respect to conventional tolls when there is a queue of 20 vehicles. For a queue of only one vehicle, the savings is 11% (10). Bartin *et al.* (11) presented a microscopic simulation-based estimation of the spatio-temporal change in air pollution levels as a result of ETC deployment on the New Jersey Turnpike. Results showed that in the short term, ETC deployment would reduce overall network air pollution; but in the long term, its benefits would not be enough to compensate for the increase in main-line air pollution due to annual traffic growth (11). Most recent studies focus on ORT technologies and their air pollution impacts. Klodzinski *et al.* (12) analyzed the benefits of ORT at a real toll plaza in Orlando by collecting data prior to, during, and after the building phase. The analysis showed an average delay reduction of 49.8% for manual cash customers and 55.3% for automatic coin machine customers; the speed in the ETC express lanes increased by 57% (12). Lin & Yu (13) developed a methodology based on air dispersion models to assess ORT air quality. The implementation of ORT can reduce the CO levels by up to 58% (13). Other studies have focused on truck-only toll (TOT) lanes as a means of improving the flow of trucks, reducing freeway congestion and controlling climate change impacts. An application of TOT lanes in the Atlanta area suggests that TOT lanes as a freeway management strategy could have significant benefits with respect to CO₂ emissions, offering a 60% reduction (14). Liu *et al.* (15) proposed an operational model for toll stations integrated with a modal emissions model. Scenarios were defined to analyze the impact of ETC lanes with respect to manual booths lanes. In ETC lanes, the main benefits are the reduction of delays by 55%, of fuel consumption by 48%, and of emissions by 51.78% with respect to manual payment lanes (15).

In conclusion, some studies have investigated the impact of the application of ITS technologies at toll plazas as a way to reduce emissions and atmospheric pollutants. However, the studies which examine ITS applications on toll road networks are still largely focused on discrete applications that evaluate specific impacts rather than proposing management methodologies to evaluate the climate change impacts of different toll collection systems on toll road networks.

INTEGRATED METHODOLOGY FOR THE EVALUATION OF THE CARBON FOOTPRINT OF TOLL PLAZAS

The physical layout and operation of a toll plaza offers an approaching vehicle different lanes to choose from, depending on the payment system selected. An integrated methodology is proposed here for use in evaluating the energy consumption and CO₂ emissions of three toll collection systems – MANUAL, ETC, and ORT – according to traffic demand. The stages of each system are considered, which allows for the establishment of management policies on a stage-by-stage or global basis. The framework of the methodology is shown in Figure 1.

A MANUAL lane has three steps, regardless of whether the payment is automated or made with cash: deceleration stage, service stage with stop, and acceleration stage. During peak periods, a vehicle may be forced to wait at the entrance of the toll plaza, creating a possible additional step: the queuing stage. In an ETC system, the energy consumption formula has only two phases, deceleration and acceleration stage. ORT systems eliminate barriers altogether and allow vehicles to travel through toll collection points without deceleration, thereby maintaining their speed and trajectory.

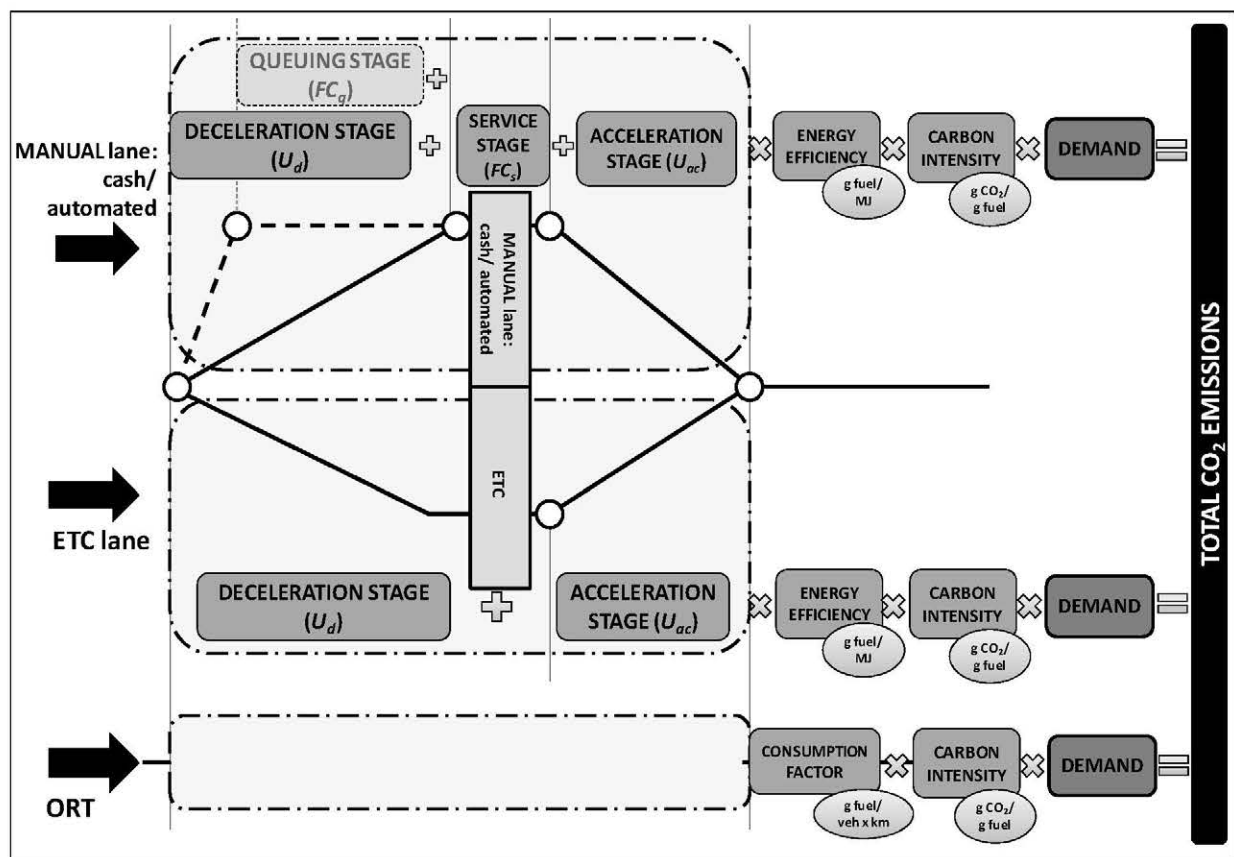


FIGURE 1 Framework for estimating CO₂ emissions at toll plazas by toll collection system.

ORT systems do not produce any perturbation in traffic flow. Therefore, we have developed an *ad hoc* methodology for the estimation of emissions applied to the case of the Spanish toll road network and fleet characteristics (16). This methodology is based on COPERT IV, which is an European tool for the calculation of emissions from the road transport sector (17).

In order to calculate energy consumption and CO₂ emissions of MANUAL and ETC systems, two different approaches have been followed, one for acceleration (U_{ac}) and deceleration (U_d) stages and another for stop&go stages, service stage (FC_s) and queuing stage (FC_q).

Firstly, for acceleration and deceleration stages, a mechanical "bottom-up" model has been applied (14). This model has been widely used and verified in transport research (17-19); as it takes into account both road design and vehicle characteristics. Moreover, a mechanical model improves the quality of the assessment and enables evaluation of the energy consumption impacts of new policy measures regarding infrastructure and modal shift (19).

The energy consumption model used here is based on the form of work energy, and is the product of the distance traveled and the external force that opposes vehicle motion. The initial model consists of five groups of external forces:

$$U_k = U_g + U_i + U_r + U_a + U_c \quad (1)$$

where U_k is the total energy consumption in each stage k (deceleration d or acceleration ac stages) and is expressed in mega-joules per vehicle. It depends on the energy consumption due to gravitational losses, U_g ; the consumption due to inertial acceleration/deceleration, U_i ; the consumption due to rolling resistance, U_r ; the consumption due to aerodynamic drag, U_a ; and the consumption due to cornering losses, U_c . As toll plazas are straight sections of road with no significant gradient, the energy consumption contribution due to cornering and gravitational losses have been considered null. The final expression of the mechanical model is as follow:

$$U_k = [C_i \times M_{fr} \times a \times d_i + C_r \times P \times \cos\theta \times d_r + (1/2) \times \rho \times C_d \times A_f \times v_r^2 \times d_a] \times (1/\eta_{motor}) \times e_v \quad (2)$$

where C_i is the mass transfer coefficient correction factor, M_{fr} is the rotational mass of the vehicle (kg), a is the rate of acceleration or deceleration (m/s^2), C_r is the rolling resistance, P is the vehicle weight ($kg \cdot m/s^2$) – product of the vehicle mass (m , kg) and acceleration of gravity (g , constant equal to 9.8 m/s^2) – θ is the road gradient (m/m), ρ is the air density ($1,225 \text{ kg/m}^3$), C_d is the drag resistance, A_f is the frontal area of the vehicle (m^2), v_r is the relative velocity of the vehicle taking into account the effect of wind (m/s), and v is the vehicle velocity (m/s) (19). These respective external forces, which determine the energy consumption, are multiplied by the effective distances traveled (m): inertial d_i , rolling d_r , and aerodynamic d_a . Finally, the efficiency of the engine η_{motor} and the wind exposure factor e_v are applied.

Secondly, for stop&go stages Fuzzi et al. (20) found that a stop of three minutes at a toll road with its engine running consumes and pollutes the equivalent of one kilometer in route. This assumption has been taken into consideration to calculate the CO₂ emissions during the waiting time in service stage, FC_s , and queuing stage, FC_g .

For both methods, the Spanish fleet has been classified in 6 categories: passenger cars, vans, motorcycles, rigid trucks, articulated trucks, and buses. Average values obtained from manufacturers have been taken into account for the specific characteristics of each vehicle category, namely their weight, dimensions and technical characteristics. In this study, wind has not been taken into consideration. In order to ensure a better validation and application of the mechanical model, a field data collection was carried out aboard a vehicle. The driving conditions and physical characteristics of toll plazas were obtained in that field test that will be described below.

ITS CONTRIBUTIONS TO THE REDUCTION OF THE CARBON FOOTPRINT OF TOLL PLAZAS

The following section deals with the management strategies which are proposed for the case study of toll plazas on the AP-6 motorway. The proposed methods for estimating CO₂ emissions at toll plazas are applied to several scenarios which considered different management strategies for optimizing the carbon footprint of toll plazas.

Description of the Case Studies

The AP-6 corridor has been selected as a case study for testing the methodology proposed in this research. This toll motorway is located just northwest of Madrid, Spain. Its total length is 69.6 km, divided into three toll sections and two free sections. Its annual average daily traffic (AADT) is significantly higher than the average of the Spanish toll roads: 27,123 veh/day, of which 13% are heavy vehicles. However, it should be noted that AADT is not constant and varies according to toll section, time of day and day of the week (6).

The test site included two main-line AP-6 toll plazas, San Rafael and Sanchidrián, located along the motorway at kilometer points 60.5 and 102.5 respectively.

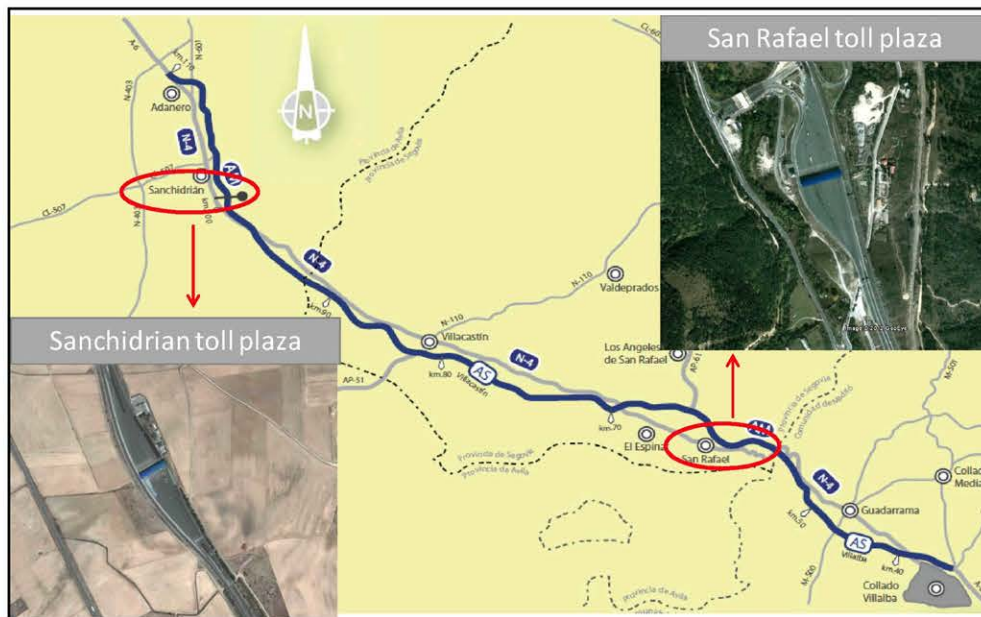


FIGURE 2 Location of the San Rafael and Sanchidrián toll plazas on the AP-6 motorway.

Traffic volume data for the two toll plazas have been provided by the AP-6 toll motorway concessionaire, ABERTIS. Traffic volume differences between them are significant. San Rafael has an AADT of 16,043 veh/day, 21% of which is heavy vehicles, on working days, and 18,728 veh/day with 13% heavy vehicles, on non-working days. Traffic volume in Sanchidrián toll plaza is lower: on working days, its AADT is 8,095 veh/day, of which 13% are heavy vehicles, and on non-working days it is 10,209 veh/day with 5% heavy vehicles. It should be noted that heavy vehicles include rigid trucks, articulated trucks and buses; light vehicles are passenger cars, vans and motorcycles.

Hourly traffic distribution is similar in both toll plazas, with two peak periods in an average day. In the case of light vehicles, traffic volume is about the same in the early hours of the morning. But from 11:00 am the traffic increment in San Rafael is higher than in Sanchidrián as is shown in Figure 3. Hourly traffic distribution of heavy vehicles is higher in San Rafael especially at middle of the day.

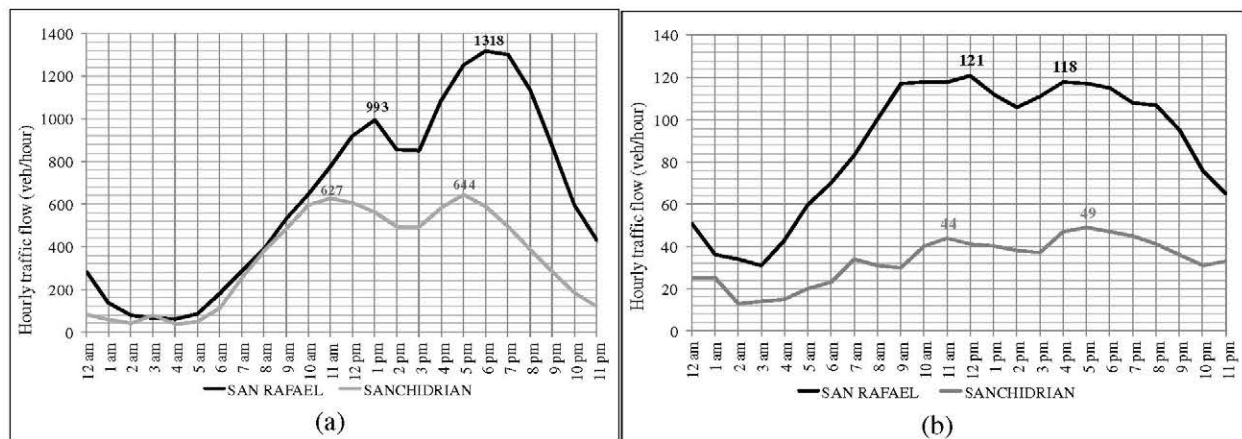


FIGURE 3 Hourly traffic distribution of (a) light vehicles and (b) heavy vehicles in both toll plazas, 2010.

The toll collection systems in both toll plazas include MANUAL lanes and ETC lanes. In the current study, the manual collection systems include cash and card payment. As shown in Table 1, light vehicles generally use the manual toll systems, with a more than 85 % share for working days and around 90% for non-working days. The heavy vehicles distribution by toll collection system is also very similar at both toll plazas; ETC lanes are used much more by heavy than light vehicles.

TABLE 1 Share of Toll Collection Systems Use by Vehicle Type and Day of the Week, 2010

	Toll Collection System	Working Days			Non-working Days		
		Light Vehicles (%)	Heavy Vehicles (%)	Total	Light Vehicles (%)	Heavy Vehicles (%)	Total
San Rafael	Manual	86	47	79	90	46	87
	ETC	14	53	21	10	54	13
	Total	82	18	100	93	7	100
Sanchidrián	Manual	88	49	83	91	56	88
	ETC	12	51	17	9	44	12
	Total	87	13	100	95	5	100

Management Strategies

The suggested management strategies follow a scenario-building approach (see Table 2). Two different strategies have been proposed: toll collection systems management and queue management.

a. The toll collection systems management strategy considers three different types of payment at both toll plazas. The current management situation (see Table 1) is considered as a reference scenario to the three new ones: MANUAL, ETC and ORT. The comparison to the reference scenario evaluates the increase or decrease in CO₂ emissions. The methodology is applied to the scenarios on both working and non-working days.

b. The second management strategy deals with queue management. In this case, the real situation during the test at San Rafael toll plaza is evaluated by comparing a reference scenario (*R-Congestion*), which includes a distribution of time spent queuing, with a scenario in which lane management is applied and queuing time is eliminated.

TABLE 2 Alternative Scenarios and Management Strategies at Toll Plazas of AP-6 Motorway

MANAGEMENT STRATEGIES	SCENARIOS		DEFINITION
A. Toll Collection Systems	San Rafael	Sanchidrián	
	R-0	C-0	Current management of the toll plazas (see Table 1). Assumes no traffic congestion. Reference scenarios. All other scenarios from toll collection systems management strategy will be compared to these data.
	R-MANUAL	C-MANUAL	All traffic flows use manual toll collection systems. Assumes no traffic congestion.
	R-ETC	C-ETC	All traffic flows use ETC systems. Assumes no traffic congestion.
	R-ORT	C-ORT	All traffic flows use ORT systems. Assumes no traffic congestion.
B. Queue	R-Congestion		Reference scenario. Real situation at toll plaza taking into account time spent waiting in queues. The scenario from queue management strategy will be compared to these data
	R-Non Congestion		Assumes no queue time through lane management.

Data collection in the toll plaza

A field data collection was carried out at the San Rafael toll plaza to apply the mechanical model. The main purpose of this data collection was to measure the physical characteristics of the toll plazas, the driving conditions, and the queuing time at the entrance of toll plaza during peak-periods. The physical characteristics and driving conditions obtained from the test have been applied to both San Rafael and Sanchidrián. The field data collection was performed from 9:00 am to 2:00 pm on Wednesday, September 14, 2011, in order to achieve the traffic patterns and distribution of the use of toll booths. To estimate queue time, the test period was divided into five hour-long intervals. The peak queue time was observed at midday, with a waiting time of 116 seconds. The results obtained for the MANUAL and ETC toll collection systems at the San Rafael plaza are shown in Table 3.

TABLE 3 Data-Collection Parameters at San Rafael Toll Plaza

	Parameters	Units	Toll Collection System	
			MANUAL	ETC
Physical Characteristics	Deceleration distance	m	389.8	389.8
	Accelerate distance	m	394.05	394.05
Driving Conditions	Initial velocity	m/s	22.74	23.61
	Velocity during payment process	m/s	0	8.68
	Final velocity	m/s	19.10	20.31
	Deceleration	m/s ²	1.08	0.78
	Acceleration	m/s ²	0.94	0.72
	Deceleration time	s	24.26	20.76
	Acceleration time	s	24.50	16.79
	Service time	s	12.68	0
	Average queue time	s	73	0

According to the data recorded the same day by the toll motorway concessionaire, the average traffic volume at San Rafael toll plaza was 782 vehicles per hour, of which 19% were heavy vehicles, and the usage share of each payment system –MANUAL and ETC – was 78% and 22%, respectively.

RESULTS

The application of the emissions models allows us to evaluate the carbon footprint of the different proposed scenarios as described in Table 2. Results are presented for each management strategy.

a. Carbon Footprint Assessment depending on toll collection system

CO₂ emissions in tons per day are determined by toll collection system with annual data from the AP-6 concessionaire, 2010. The CO₂ savings results allow the proposed scenarios to be compared.

The findings reveal that the application of new toll collection technologies is an effective management strategy. ORT systems are particularly effective and can lead to CO₂ emissions savings of up to 70%. This clearly justifies this type of toll system which eliminates barriers and collects electronic payments without affecting highway speed. The CO₂ emissions savings achieved by ETC systems implementation come to more than 20%. In contrast, the maintenance of conventional toll booths as the only payment system supposes an increase in energy consumption and CO₂ emissions. In fact, on working days, CO₂ emissions were increased by almost 6% at the San Rafael toll plaza and by almost 5% at Sanchidrián. On non-working days, this increment is smaller at both toll plazas due to a decrease in the volume of heavy vehicles (about 3%). The comparison of each scenario with its respective reference scenario is shown in Table 4.

TABLE 4 CO₂ Emissions per Day at AP-6 Toll Plazas and CO₂ Annual Savings By Scenario

Scenarios	Working Days		Non-working Days	
	CO ₂ Emissions (tCO ₂ /day)	CO ₂ Annual Savings (%)	CO ₂ Emissions (tCO ₂ /day)	CO ₂ Annual Savings (%)
San Rafael	R-0	11.52	11.43	
	R-MANUAL	12.19	11.84	-3.56%
	R-ETC	9.01	8.70	23.92%
	R-ORT	3.44	3.46	69.74%
Sanchidrián	C-0	5.43	6.10	
	C-MANUAL	5.69	6.31	-3.31%
	C-ETC	4.19	4.63	24.19%
	C-ORT	1.63	1.85	69.68%

b. Impact of Queue Management at Toll Plazas on Carbon Footprint

The queue time management results obtained from the San Rafael test are shown in Figure 4. During the test, queues were produced by the manual toll collection systems while no waiting times were observed in the ETC lanes. Figure 4 (a) shows the hourly traffic distribution of manual lanes and the average waiting times for each hourly interval of the Wednesday, September 14, 2011. Although the traffic volume is similar from 11:00 am to 1:00 pm, the average waiting time decreases from 12:00 pm on, due to the opening of additional manual toll lanes (lane management).

According to the R-Non Congestion scenario (no queue time through lane management), the highest CO₂ emissions savings are produced during the peak period, around 16% as shown in Figure 4 (b).

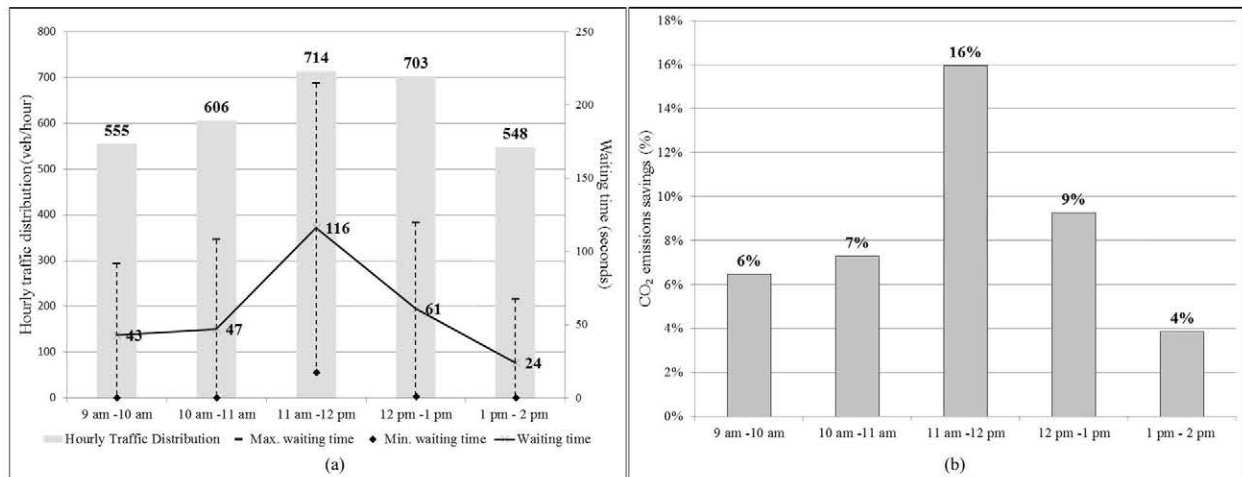


FIGURE 4 San Rafael manual lanes: (a) queue time and hourly traffic distribution, (b) CO₂ emissions savings.

CONCLUSIONS AND RECOMMENDATIONS

This research is focused on the operational characteristics and climate change impacts of ITS technologies at toll plazas. Toll plazas are key for reducing the GHG emissions associated with traffic flow and for improving toll road operations. Most of the previous studies had examined discrete ITS applications that evaluated air pollution impacts. However, these studies are still largely focused on discrete applications rather than proposing management methodologies to evaluate the climate change impacts of different toll collection systems. This study proposes an integrated methodology for carbon footprint assessment of different toll collection systems – MANUAL, ETC and ORT– at toll plazas of a motorway network. This methodology considers the four driving stages – deceleration, service time, acceleration, and queuing – of the different toll collection systems. In order to validate this methodology, management strategies were proposed for two case studies on the Spanish AP-6 toll motorway. For the two main-line toll plazas, different scenarios were proposed which take into account the toll collection systems and queuing management.

Final energy consumption is closely associated with the speed changes and driving conditions of a vehicle. The results of this study show that CO₂ emissions can be reduced by using new technologies in toll collection systems. The most significant savings (about 70%) are achieved by the implementation of ORT systems. That is because vehicles are able to maintain full highway speed when they pay the toll. Therefore, ITS are the future of the decarbonization of toll plazas as they allow for toll payment without slowing down or changing the trajectory of a vehicle. Manual toll systems, on the other hand, are the least efficient system due to the speed changes and stopping stages they require. Lane management at toll plazas reduces the waiting time at the entrance and thus involves an energy consumption savings.

In Spain, the incorporation of ETC systems in the toll road network is being consolidated but its share is still less than that of manual toll systems. It is necessary to promote measures that will increase the usage of intelligent toll collection systems. A toll system without barriers – ORT – would lead to some 4,400 tons of CO₂ savings per year on the AP-6 motorway.

In conclusion, many new technologies aim to respond to the reality of transport needs. It has been proved that the most advanced ITS the highest efficiency to reduce climate change impacts and to improve energy savings. The integrated methodology proposed in this study enables the assessment of energy consumption and CO₂ emissions of toll plazas – stage-by-stage or globally– by toll collection system. It provides an efficient management tool for toll plazas. The wider application of new technologies will lead to more a sustainable management of toll plazas in the future.

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